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Adaptive Mathematical Morphology for Range Imagery

Jacques G. Verly and Richard L. Delanoy

Abstract—**We explore the application of *adaptive* (i.e., data-dependent) mathematical morphology techniques to *range* imagery, i.e., the use of structuring elements that automatically adjust to the grayscale values in a range image in order to deal with (e.g., extract or eliminate) features of known physical sizes.**

I. Introduction

Often, the output of a mathematical-morphology (MM) operation [1] (either binary or grayscale) describes how well a shape, called a *structuring element* (SE), either *fits* or *does not fit* inside a local image feature.

Whereas the SE's used in most applications remain constant as they probe an image, there are situations where SE's must change their size, orientation, and/or shape during probing. If these changes are determined *a priori*, independently of the data, the SE's can be said to be *space variant*. If the change is made on the basis of the value(s) of one or more pixels around the pixel being probed, the SE's can be said to be *data dependent* or *adaptive*. We are aware of only a few papers dealing with space-variant SE's, e.g., [2] (also in [3]) and [4], and of none dealing with adaptive SE's.

Since range imagery [5] contains significant shape information and since MM deals with shape in images, it is also surprising that so few papers have been written on the application of MM to range imagery (examples are [6]–[10]).

Since "angle-angle" range images are subject to the usual perspective distortions, the apparent length of a feature in such images is a function of the feature range. With range available at each pixel, one can simultaneously process (e.g., extract or eliminate) all the differently-scaled instances of the feature or object of interest by adapting the sizes of the SE(s) to the local range.

For simplicity, we will assume that all SE's of interest become fully determined when their scalable x size and y size are specified (x and y, respectively, refer to the horizontal and vertical image axes). In other words, we assume that adapting an SE to range simply amounts to finding the appropriate x and y sizes. Examples of useful SE's that have such properties are the rectangular and ellipsoidal SE's (either binary or grayscale). Note that, for this class of SE's, changing the x and y sizes can in some cases cause a spatial compression/expansion of the pattern (either binary or grayscale). The goal of this paper is to develop a systematic, practical methodology for designing and applying adaptive SE's for range imagery under the constraints just described.

II. Principles

Let us consider a range image R of a scene S. The grayscale value r_i associated with each pixel is related to the distance r_m (say, in meters) between the corresponding patch of S and the sensor by

$$r_i = \left[\frac{r_m - r_0}{b} \right] \tag{1}$$

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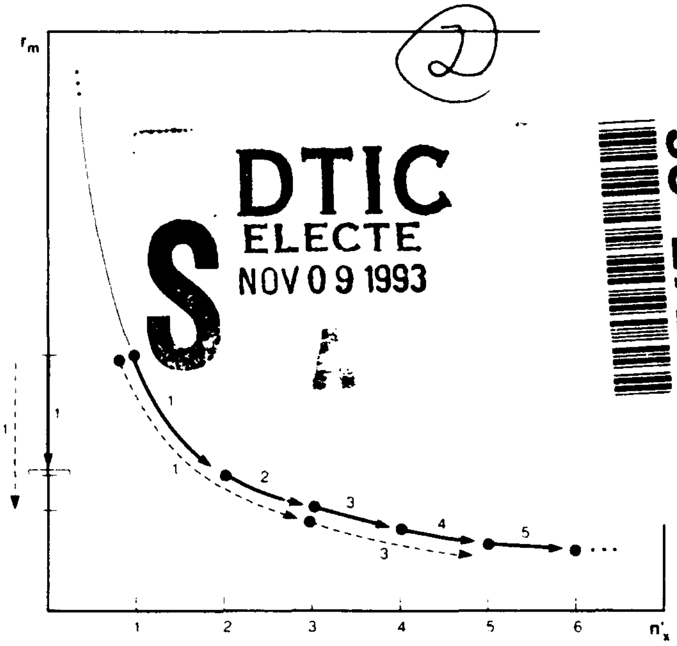

Fig. 1. Range intervals associated with integer-length SE's when the SE's *must fit* inside a feature.

where r_0 is a range offset corresponding to the grayscale value of 0, b is the range quantization value, and $[x]$ is the integer part of x.

The length n'_x in units of pixels of a horizontal feature F (in R) that has an actual length of x_m meters (in S) and is located at a distance of r_m meters from the imaging sensor is given by the small-angle approximation

$$n'_x = \frac{x_m}{r_m \alpha_x} \tag{2}$$

where α_x is the horizontal angular width (in radians) of a pixel. This expression can also be used to find the x dimension n_x (in pixels) of the SE required to detect F in R (for convenience, we can temporarily focus on the case of horizontal, rectangular, 1-pixel high SE's). Notice that we use primed symbols like n'_x to denote arbitrary lengths in units of pixels, and unprimed symbols like n_x for lengths that are an integer number of pixels.

From the functional dependency of r_m upon n'_x for fixed α_x and x_m (e.g., as in Fig. 1), we observe the following.

First, consider SE's that *must fit* inside F in R. Such SE's will be said to be of type MF. For example, a SE used in an opening with the intent of *preserving* a protrusion must be of type MF; ditto for closing and intrusion. A fixed-length SE designed to fit inside F at a given range will fit in the same F at a shorter range, but not at a longer range. Since the localization of F based on a fixed-length SE becomes less sharp as the range decreases, one should switch to the next larger size SE as soon as its design range is reached. In summary, in the case of MF-type SE's, the range interval where a given SE can be used is from (and including) its associated range (i.e., the range at which it fits exactly in F) *down to* (but excluding) the design range of the *next larger* SE. For example, when all integer-length SE's are available, the *semi-open* range interval for the SE corresponding to $n_x = 1$ is obtained from the solid curve segment labeled 1 in Fig. 1 (the interval is shown along the r_m-axis). Pixels with ranges corresponding to $n_x = 0$ should not be processed at all.

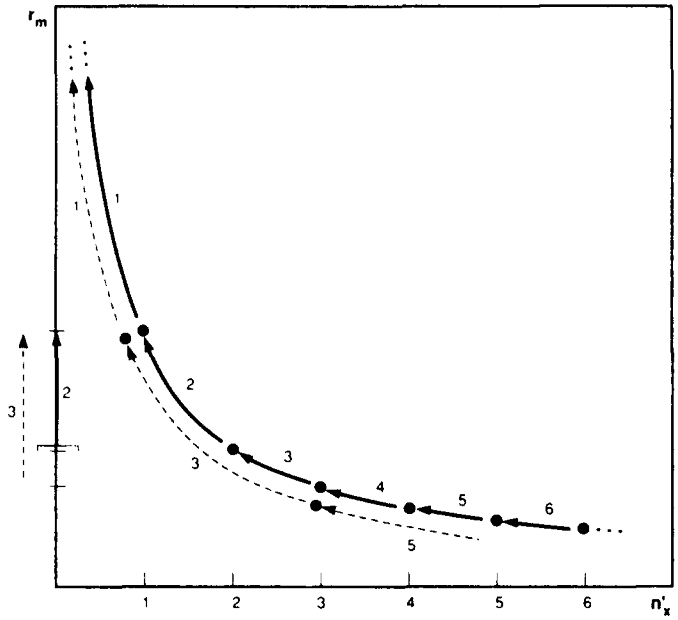

Fig. 2. Range intervals associated with integer-length SE's when the SE's *must not fit* inside feature.

Second, consider SE's that *must not fit* inside F in R. Such SE's will be said to be of type MNF. For example, a SE used in an opening with the intent of *eliminating* a protrusion must be of type MNF; ditto for closing and intrusion. Here, the range interval where a given SE can be used is from (but excluding) its associated range (i.e., the range at which it fits exactly in F) *up to* and including the design range of the *next smaller* SE (Fig. 2).

In practice, it may not be feasible to use all the sizes n_x that are necessary to cover the total range interval of R. The dashed lines in Figs. 1 and 2 show the range intervals and the corresponding SE sizes for the hypothetical case where only the *odd* sizes n_x are available.

III. Implementation

Denote the minimum and maximum values of R by $r_{A,i}$ and $r_{B,i}$, where i is a reminder that these numbers are integers. Using (1), one can find the limits of the span $[r_{A,m}, r_{B,m}]$ of actual range values (in meters) in R, i.e.,

$$\begin{cases} r_{A,m} = r_0 + r_{A,i} b \\ r_{B,m} = r_0 + (r_{B,i} + 1) b . \end{cases}$$

A. Selection of Necessary SE's

Using (2), one finds that the required interval of sizes n'_x is $[n'_{x,\min}, n'_{x,\max}]$, with

$$n'_{x,\min} = \frac{x_m}{r_{B,m}\alpha_x}, \quad n'_{x,\max} = \frac{x_m}{r_{A,m}\alpha_x}.$$

Assuming that the only SE sizes available are those in the ordered set

$$N_x^* = \{n_{x,k} \mid k = 1, K_x^*; n_{x,1} = 0; n_{x,k} < n_{x,k+1}\}$$

where K_x^* is the number of available sizes, the corresponding interval of integers n_x is $[n_{x,\min}, n_{x,\max}]$ where the limits are as follows.

1. For SE's of type MF:

$$\begin{cases} n_{x,\min} = \text{largest integer in } N_x^* \\ \qquad\qquad \text{less than or equal to } n'_{x,\min} \\ n_{x,\max} = \text{largest integer in } N_x^* \\ \qquad\qquad \text{less than or equal to } n'_{x,\max} . \end{cases}$$

2. For SE's of type MNF:

$$\begin{cases} n_{x,\min} = \text{smallest integer in } N_x^* \\ \qquad\qquad \text{strictly greater than } n'_{x,\min} \\ n_{x,\max} = \text{smallest integer in } N_x^* \\ \qquad\qquad \text{strictly greater than } n'_{x,\max} . \end{cases}$$

Thus the set of SE's that can be called upon is the ordered subset

$$N_x = \{n_{x,k} \mid k = 1, K_x; n_{x,k} \in N_x^*; \\ n_{x,\min} \le n_{x,k} \le n_{x,\max}; n_{x,k} < n_{x,k+1}\}$$

of N_x^*, where $K_x \le K_x^*$ is the maximum index k needed.

B. Selected-SEs' Range Intervals in Meters

Denoting the actual range (in meters) associated with each $n_{x,k}$ in N_x by $r_{x,k,m}$, with

$$r_{x,k,m} = \frac{x_m}{n_{x,k}\alpha_x}$$

it can be shown that the lower and upper limits (in meters) of the *semi-open* interval $[r_{x,L,k,m}, r_{x,H,k,m}]$ are as follows.

1) For SE's of type MF:

$$r_{x,L,k,m} = \begin{cases} r_{x,k+1,m} & \text{if } k < K_x \\ r_{A,m} & \text{if } k = K_x \end{cases}$$

$$r_{x,H,k,m} = r_{x,k,m} .$$

2) For SE's of type MNF:

$$r_{x,L,k,m} = r_{x,k,m}$$

$$r_{x,H,k,m} = \begin{cases} r_{x,k-1,m} & \text{if } k > 1 \\ r_{B,m} & \text{if } k = 1 . \end{cases}$$

C. Selected-SEs' Range Intervals in Range Integers

Expressing interval limits in terms of range integers (instead of meters) can speed up the repeated comparison of pixel grayscale levels to the various intervals. Introducing

$$r'_{x,k,i} = \frac{r_{x,k,m} - r_0}{b}$$

one can show that the upper and lower limits (in range integers) of the *closed* interval $[r_{x,L,k,i}, r_{x,H,k,i}]$ associated with each size $n_{x,k}$ in N_x are as follows.[1]

1) For SE's of Type MF:

$$r_{x,H,k,i} = \text{largest integer smaller than or equal to } r'_{x,k,i}$$

$$r_{x,L,k,i} = \begin{cases} r_{x,H,k+1,i} + 1 & \text{if } k < K_x \\ r_{A,i} & \text{if } k = K_x . \end{cases}$$

2) For SE's of type MNF:

$$r_{x,L,k,i} = \text{smallest integer strictly greater than } r'_{x,k,i}$$

$$r_{x,H,k,i} = \begin{cases} r_{x,L,k-1,i} - 1 & \text{if } k > 1 \\ r_{B,i} & \text{if } k = 1 . \end{cases}$$

D. General Implementation Strategy

So far, we have focused on the x dimension of an SE and on the particular case of a 1-pixel high horizontal SE. Of course, the argument can be identically repeated for the y dimension and for a

[1] The limits $r_{x,L,k,i}$ and $r_{x,H,k,i}$ are derived independently of their counterparts $r_{x,L,k,m}$ and $r_{x,H,k,m}$.

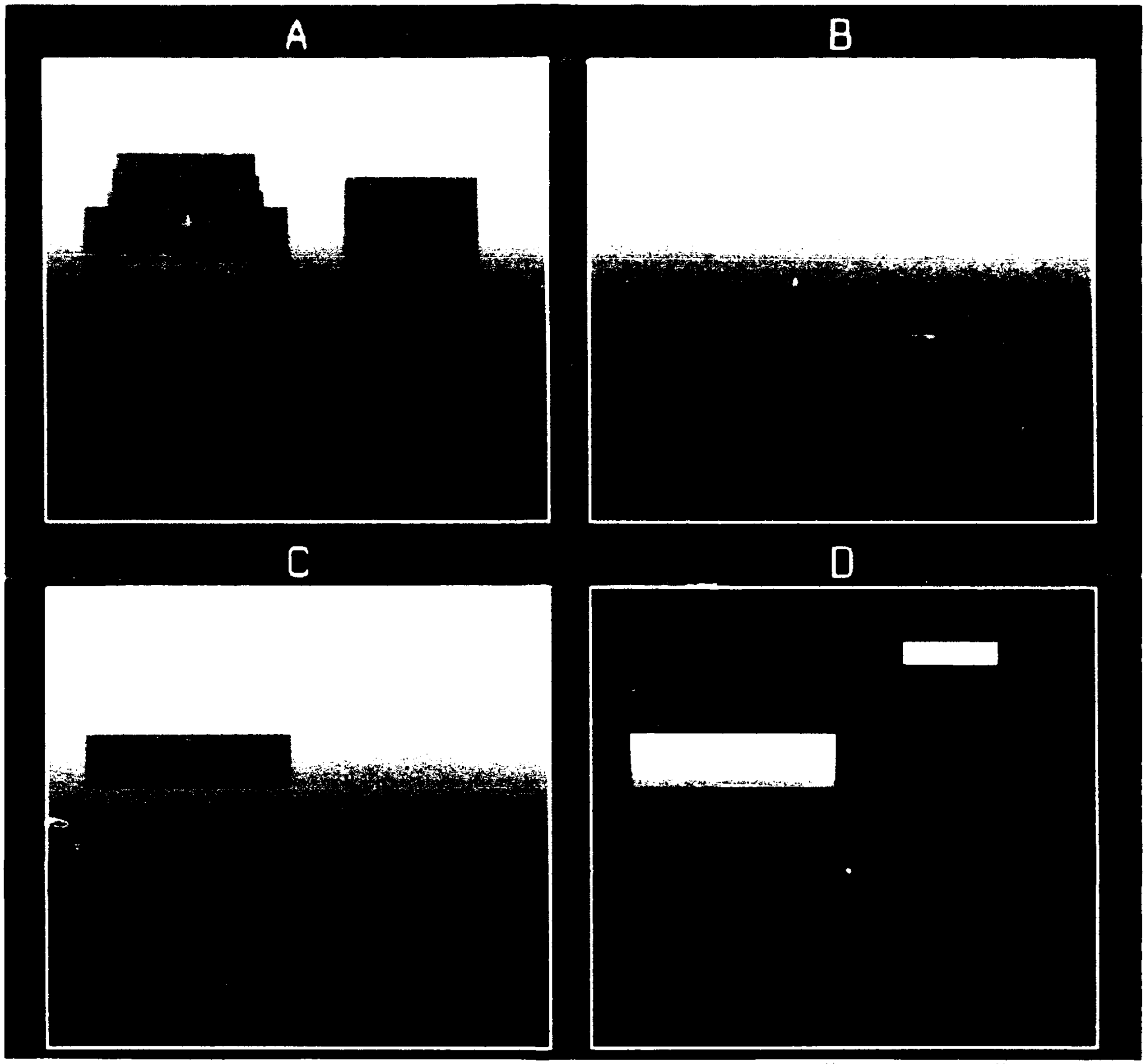

Fig. 3. Extraction of tank bodies from a synthetic range image: (A) range image R, (B) closing $R^{H_{7.0}}$, (C) closing $R^{H_{3.0}}$, (D) output image $B = R^{H_{7.0}} - R^{H_{3.0}}$.

1-pixel wide vertical SE. In the case of an arbitrary SE, one must deal with both dimensions simultaneously.

The general strategy for efficiently implementing adaptive MM algorithms is to (a) determine the sets N_f and N_g of applicable SE sizes, (b) find the interval $I_{f,k}$ ($I_{g,l}$) of range values (either in meters or in range integers) each SE size $n_{f,k} \in N_f$ ($n_{g,l} \in N_g$) applies to, (c) denote by $I_{k,l}$ the (possibly empty) range interval that is common to $I_{f,k}$ and $I_{g,l}$ and associate with it the available SE with sizes $n_{f,k}$ and $n_{g,l}$, and (d) perform the desired operation on the image of interest by selecting the appropriate available SE at each pixel based upon the range at that pixel. This last step may be implemented in a variety of ways, including in parallel, e.g., with one processor per applicable SE. Once again, one should stress that the processing will depend upon the type of each SE of interest, i.e., MF or MNF.

IV. Application

Adaptive MM is routinely used by the authors for the extraction of vehicles of known sizes from *real* low-resolution (2-6 meters) tactical laser-radar imagery. It is one of the techniques used in the XTRS system described in [11]. Here, to better demonstrate the potential of adaptive MM, we use a 2-m resolution *synthetic* image of a scene consisting of a ground plane, a background vertical wall at 1,700 m, and 3 objects: a 3.6 m-wide tank and a 2.4 m-wide box, both at 700 m, and a replica of the first tank at 1,500 m (Fig. 3(A)).

In images taken roughly at ground level, vehicles that have width w and length l produce observable silhouettes whose length should be in the approximate interval $[w, \sqrt{w^2 + l^2}]$. For the tank in Fig. 3(A), the limits of this interval for the tank body are approximately 3 m and 7 m.

An image B that highlights the tank bodies in the image R of Fig. 3(A) can be created by using the *difference-of-closings*

$$B = R^{H_{7.0}} - R^{H_{3.0}}$$

where $H_{7.0}$ is a MF-type adaptive SE designed for a feature length $x_{obj} = 7.0$ m and $H_{3.0}$ is a MNF-type adaptive SE designed for $x_{obj} = 3.0$ m (both SE's are 1-pixel high). The result is shown in Fig. 3(D). First, note that both tank bodies are correctly highlighted in spite of their different apparent widths.

This results from the fact that the visible 3.6 m physical widths of the bodies are within the allowed 3–7 m physical-size range for the visible widths of such bodies. Second, note that the box in front of the

farthest tank is not detected even though its apparent width is between those of the tank bodies. Of course, the reason is that the physical width of the box is outside the allowed range for physical body sizes. Clearly, the exact same technique would extract any number of tanks (e.g., in column), provided the tanks do not significantly overlap.

The success of our simple object extraction procedure is not only due to the well-known "sieving" properties of successive closings (or openings) with differently sized SE's [1], but also to the use of range-adaptive SE's properly designed with respect to the MF/MNF dichotomy.

V. Conclusions

In this work, we have pointed out the role of adaptive MM in the processing of range imagery. We have emphasized the importance of correctly distinguishing between, and implementing, adaptive (i.e., data dependent) SE's that either "must fit" or "must not fit" within the feature(s) of interest. It should be clear that the choice among the elements of the MF/MNF dichotomy is based on the problem at hand, and is not an intrinsic property of the MM operation used. In other words, *there is no such conclusion as* saying that MM operation X (e.g., dilation, erosion, opening, closing, etc.) should always be used with an adaptive SE designed so that it fits (or, similarly, does not fit) inside the feature of interest.

Although we have discussed adaptive MM in the specific case of range imagery, this technique is applicable to any type of image for which the distance to a scene element is available for each pixel. Such a situation occurs in laser-radar imaging where pixel-registered range and intensity images are often available. In this particular application, adaptive MM can be applied to the intensity image by using the distance information available from the range image.

The techniques presented are limited to the case where the SE's can be scaled through their x and y sizes. Clearly, the opportunity exist for developing a more general theory and methodology for designing and applying adaptive SE's to range imagery. Furthermore, the whole question of how to efficiently implement adaptive MM should be investigated in detail.

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